A DECADE OF CHANGE IN THE SKIDAWAY RIVER ESTUARY. I. HYDROGRAPHY AND NUTRIENTS

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Abstract. The Skidaway River estuary is a tidally-dominated subtropical estuary in the southeastern USA surrounded by extensive *Spartina* salt marshes. Weekly sampling at high and low tide began in 1986 for hydrography, nutrients, chlorophyll *a*, particulate matter, and microbial and plankton biomass and composition; hydrographic and nutrient data during 1986-1996 are reported here. Salinity varied inversely with river discharge and exhibited variability at all time scales but with no long-term trend. NO_3, NH_4, PO_4, $Si(OH)_4$, and DON exhibited steady increases in minimum, mean, and maximum concentrations; mean concentrations increased ca. 50-150% during the decade. Major spikes in organic and inorganic nutrient concentrations coincided with significant rainfall events; concentration increased hyperbolically with rainfall. Land use is apparently altering nutrient loading over the long term (months-years), and superimposed on this are stochastic meteorological events that accelerate these changes over the short term (days-weeks).

INTRODUCTION

Data from NOAA indicates that coastal counties represent 11% of the area of the United States but contain half of the national human population. Coastal communities in general are projected to increase 15% by 2010, with some of the highest growth rates expected to occur in coastal areas of the southeastern U.S. (DeVoe and Kleppel, 1995). As larger numbers of people inhabit and visit these regions, demand for development and infrastructure will continue to climb, and associated changing land use patterns threaten to significantly reduce environmental quality. At the time this study was initiated, estuarine waters of Georgia were considered relatively pristine with respect to environmental quality issues such as eutrophication, contamination, and disease-causing organisms (NOAA, 1996). However, land use impacts may begin without obvious warning signs, and become difficult to reverse by the time they are documented. Accordingly, a weekly sampling program was begun in 1986 at a station in the Skidaway River estuary, with the intent to establish a database on patterns in hydrography, nutrient concentrations, and suspended particulate matter, including chlorophyll *a*, POC, PON, and various trophic and functional groups of auto- and heterotrophic plankton. The first decade of hydrographic and nutrient data are reported here.

MATERIALS AND METHODS

Study Site. The Skidaway River Estuary (Fig. 1) is a typical southeastern U.S. estuary surrounded by extensive stands of salt marsh, and is tidally dominated with comparatively small freshwater inputs except following periods of heavy rainfall, when it receives freshwater from the south (Ogeechee River) and the north (Savannah River, via the upper Wilmington River). The Savannah and Ogeechee Rivers drain large areas of the Piedmont and Coastal Plain. Skidaway River, Wilmington River, and Wassaw Sound estuarine system are considered contiguous because of the

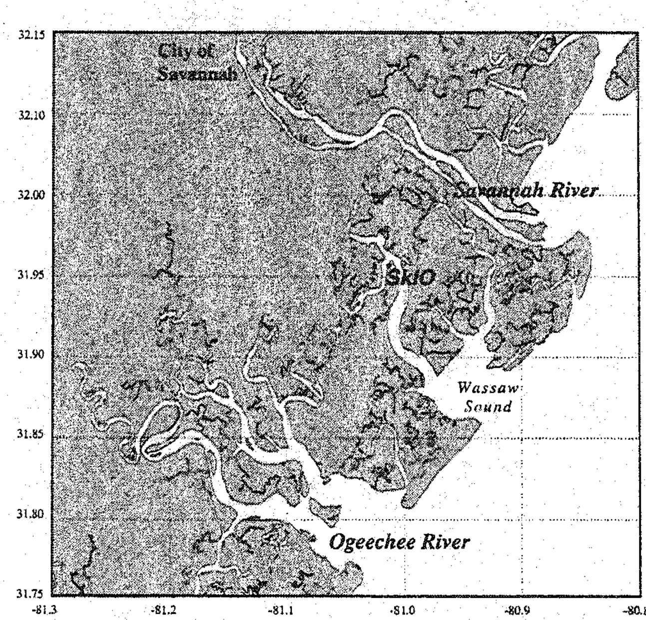

Figure 1. Study site.

extensive tidal excursion every six hours. These waters are turbid, well-mixed, and very productive, as is the surrounding salt marsh.

Sampling Procedures. Sample collection was begun in August 1986. Samples were collected from surface waters adjacent to the dock of the Skidaway Institute of Oceanography using an acid-cleaned bucket. One day ca. every week, samples were collected on consecutive high and low tides. Samples were collected for measurement of temperature, salinity, one organic (dissolved organic nitrogen: DON) and four inorganic nutrients [PO_4, $Si(OH)_4$, NH_4, and NO_3+NO_2, hereafter referred to as NO_3]. Nutrient samples were gently pre-filtered through pre-rinsed Whatman GF/F filters; no corrections for humic materials were used. Inorganic nutrient concentrations were determined using automated procedures on a Technicon AutoAnalyzer II (see Verity et al., 1993). Total dissolved nitrogen (TDN) was determined using persulfate digestion, and DON was calculated as the difference between TDN and summed inorganic nitrogen (Valderrama, 1981). The same sampling methods and analytical procedures were used throughout the ten year sample period. Daily rainfall was measured by the National Weather Service at the Savannah International Airport. Daily discharge of the Ogeechee River at Eden, Georgia, a nontidal site 40 km upstream from where the Skidaway River joins the Ogeechee River, was measured or (occasionally) estimated by the U.S. Geological Survey from gage height records.

RESULTS

Water temperature varied from maxima of 30-33 °C in summer to minima of 6-12 °C in winter. Years with lower winter temperature minima were generally followed by lower summer maxima, and likewise milder winters were followed by warmer summer water temperatures. No evidence was found for decadal scale trends in mean, maximum, or minimum water temperature. In contrast, considerable seasonal, annual, and interannual variations were observed in temporal patterns of salinity. The typical annual salinity cycle included winter minima associated with freshets from the upstream drainage basins and summer maxima associated with warm temperatures, e.g. 1986-87. Salinity typically ranged from 18-32 PSU. However, in some years with little runoff, salinity did not decrease in winter, e.g. 1987-88. There were also rapid decreases in salinity associated with tropical storms, e.g. tropical depression Jerry in August 1995. There were extended dry periods with relatively constant and high salinities, as in 1987-89; periods of long term declines in salinity due to extended rainfall, as in 1993-94; and similar long term increases in salinity during dry spells, e.g. 1995-96. Relationships between salinity and Ogeechee River discharge could be modeled by negative exponential curves, which explained 75-79% of the variance in salinity at a given tidal stage.

All five nutrients exhibited long term trends of increasing concentrations. In 1987 (the first complete calendar year of data), NO_3 ranged from undetectable to 7.0 □M, with a mean of 1.1 □M; over the next decade, minimum concentrations increased to 0.6 □M, maximum concentrations to 10.0 □M, with a mean of 2.2 □M in 1996. Significantly, annual amplitudes in concentration also increased. In 1987, NH_4 ranged over 0.4-6.0 □M, with a mean of 1.8 □M: over the next decade, minimum concentrations increased to 1.0 □M, maximum concentrations to 10.1 □M, with a mean of 2.7 □M in 1996. As with NO_3, annual amplitudes in concentration also increased. In 1987, PO_4 ranged from undetectable to ca. 3.0 □M, with a mean of 0.6 □M: over the next decade, minimum concentrations increased to 0.3 □M, maximum concentrations to 5.1 □M, with a mean of 1.0 □M in 1996. As with NO_3 and NH_4, annual amplitudes in concentration also increased.

$Si(OH)_4$ and DON also exhibited long term increases but with important differences in patterns. In 1987, DON ranged over ca. 7.0-57.3 □M, with a mean of 20.3 □M: over the next decade, minimum concentrations increased to 37.9 □M, maximum concentrations to 69.9 □M, with a mean of 51.6 □M in 1996. Unlike NO_3, NH_4, and PO_4, annual amplitudes in DON concentration did not increase. However, the rate of increase in ambient DON concentration was ca. twice as fast as in NO_3, PO_4, and NH_4 concentrations. Similarly, $Si(OH)_4$ ranged over ca. 17.7-66.0 □M in 1987, with a mean of 44.4 □M: over the next decade, minimum concentrations increased to 44.4 □M, maximum concentrations to 84.2 □M, with a mean of 65.5 □M in 1996. Like DON and unlike NO_3, NH_4, and PO_4, annual amplitudes in $Si(OH)_4$ concentration did not increase. As with DON, the rate of increase in ambient $Si(OH)_4$ concentration was twice as fast as observed for NO_3, NH_4, and PO_4. Down-estuary transects conducted at low tide on one date in autumn of 1986, 1991, and 1996 showed a similar pattern of long-term increases in all nutrients.

Superimposed on the annual cycles and long-term trends were significant short-term spikes that most often but not always occurred in late summer. These nutrient inputs were positively correlated with occurrences of locally significant rainfall. Nutrient inputs were calculated as the change in nutrient concentration from the sample collected prior to a significant rainfall event, to the nutrient concentration in the sample collected after each event. Since utilization of inorganic and likely organic nutrients would be expected, particularly in subtropical climates, these inputs are thought to be conservative estimates. All rainfall events of 4 cm or more within a 24 hour period were examined; 51 such events were recorded over the ten year period, with six that equaled or exceeded 20 cm of rain in 24 hours.

NO_3, NH_4, PO_4, DON, and $Si(OH)_4$ all exhibited hyperbolic increases in concentration with increasing volume of rainfall; an example is shown in Fig. 2. The data were fit to a hyperbolic tangent model which included a minimum threshold: model parameter fits indicate that rainfall amounts explained 55-72% of the variance in nutrient concentrations. PO_4, NH_4, and NO_3 exhibited the lowest predicted maximum concentration changes in 24 hours (4-10 □M), with Si having intermediate maximum concentration changes (19 □M), and DON the highest changes (43 □M). The threshold rainfall amounts at which no increases in nutrient concentrations were predicted were statistically similar for all nutrients (4-5 cm/ 24 hours).

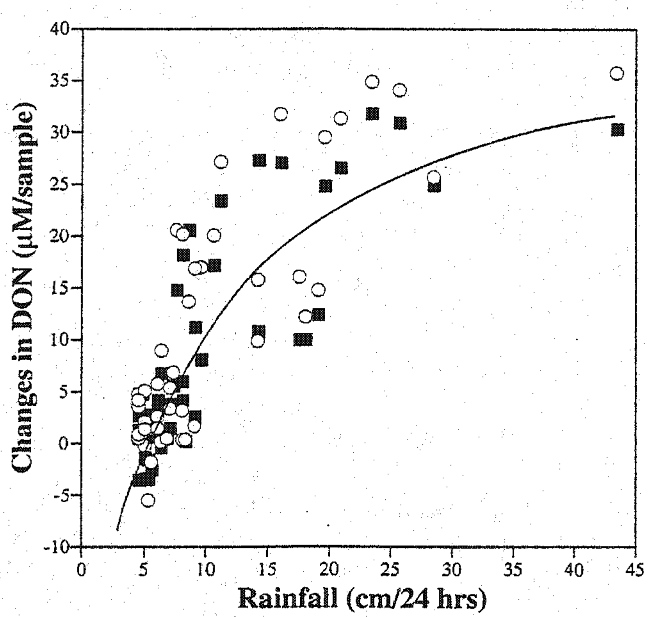

Figure 2. Relationship between significant rainfall events and the concurrent observed changes in DON concentration in the Skidaway River estuary during August 1986 through December 1996. An event was defined as 4 or more cm of rain within a 24- hour period. The change in nutrients is the difference between the concentration measured on the sample date preceding the rain event and that measured on the ensuing date. Nutrients were measured on both high (□) and low (□) tides.

Combining samples from both tides and all dates, several of the hydrographic and nutrient data were significantly correlated. Water temperature was significantly related ($P < 0.0001$) with all variables, especially with nutrient concentrations. In contrast, salinity was relatively poorly correlated with most variables even though some correlation coefficients were significant ($P < 0.05$) because of the high sample number ($n = 842$-933). Discharge was poorly related to all nutrient concentrations. Without exception, all nutrient parameters were highly correlated ($P < 0.0001$) with each other. However, these correlations averaged over the decadal dataset masked considerable interannual variability. For example, the variance in NO_3 concentrations explained by temperature ranged from 1% (in 1989) to 54% (in 1992). The range of variance in nutrient concentrations explained by temperature in a given year was 1% to 87%.

DISCUSSION

The seasonal and annual cycles of dissolved inorganic and organic nutrients showed regular annual increases with additional stochastic event-scale spikes. The observation that inorganic nitrogen and phosphate did not increase as rapidly as silicate and organic nitrogen suggests either different delivery rates or net utilizations. Current data are unable to discriminate between these possibilities, although enhanced utilization is strongly indicated (Verity, unpubl.).

Nitrogen and phosphate likely find their source in elevated supply rates from surrounding, increasingly populated environments. An important nutrient source likely is increased application and associated runoff/export of inorganic- and organic-based fertilizers from surrounding urban and upstream agricultural land use. For example, forested lands leak little NO_3 into surrounding watersheds compared to agricultural or urban landscapes (Hubertz and Cahoon, 1999). In the past 50 years the tonnage of fertilizer applied to Georgia farms doubled to 1.5M tons (Irwin et al., 1994).

Moreover, exponential growth along the coast in the number of urban lawns and golf courses (McCollister, 1993) with an annual average of 166 pounds of fertilizer per acre, may be a prime candidate for trends found in the present study. The four counties comprising the drainage basin area adjacent to the study site, Bryan, Chatham, Effingham, Liberty counties, had mean population increases of 86%, 21%, 80%, and 64%, respectively, during 1980-2000 (Boatright and

Bachtel, 2000). The population of Skidaway Island, which borders on the Skidaway River estuary, increased a staggering 458% during these two decades (Metropolitan Planning Commission, 2000).

The increases in silicate in the Skidaway River estuary are provocative: coastal development is likely adding silicate through enhanced runoff due to local deforestation and land development. However, $Si(OH)_4$ is also used in turf and ornamental herbicides, commercial plant nutritional supplements, and residential and commercial fertilizers. Whether or not the trend of increasing silicate is linked directly to the elevated loading of nitrogen and phosphorus, both apparently find their source in changes in land use due to population growth and habitat modification. Since atmospheric deposition samples contain very little PO_4 and $Si(OH)_4$, whereas the estuary clearly shows PO_4 and $Si(OH)_4$ loading after rainfall events, the rain likely acquired its nutrient load from a terrestrial source.

These data and arguments suggest that anthropogenic nutrients are reaching the estuary at rates which exceed ecosystem utilization on annual scales. At least two mechanisms for transport appear to be important. One is subtle and near-continuous, at least within the sampling time frame, because the long term concentration increases are regular and not episodic. The other mechanism is clearly discrete and apparently associated with significant rainfall events. The pattern of hyperbolic increases in estuary nutrient concentrations with increasing rainfall amounts indicates that the terrestrial source is not unlimited: with sufficient rainfall (>20 cm/24 hours) the terrestrial source is temporarily depleted and the receiving waters show little further nutrient loading. It is salient that the stochastic event loadings disappear within 1-2 sampling periods, presumably due to near-complete biological utilization (data not shown), whereas the long-term trends imply that the estuary cannot fully assimilate nutrient loadings at those longer scales.

The conduits for both the regular and the more episodic loadings may be similar or they may differ. Some component of the rainfall signal is likely to be overland sheetflow whereby the runoff directly acquires dissolved nutrients and deposits them into the estuary. This conduit is more important in urban areas where impervious surfaces are directly connected to receiving waters, as in the present study region where storm drainage is fed directly into rivers and estuaries because of the shallow water table aquifer along this coast. Indirect support for the importance of this conduit is implied by events in which the nutrient loadings occurred very quickly, e.g. within 24 hours after significant rainfall.

Another perhaps equally important conduit for nutrient delivery is via surficial groundwater discharge, which has been proposed to be 40% or more of the riverwater fluxes in the southeastern USA (Moore, 1996). Nutrient efflux into the Skidaway River estuary may be stimulated by rainfall via alteration of the groundwater hydraulic head, as observed in lakes and coastal waters elsewhere. The response time and magnitude of such pulses would depend upon sediment type, soil water content (which can be depressed due to droughts, at steady state, or saturated from excessive rain), recharge rate, and tidal stage. The relative importance of groundwater fluxes and overland flows will also change in response to land use and urbanization.

Implications. Nationally and globally, human population growth, urbanization, and nutrient loading have been closely linked (Peierls et al., 1991). Previously, estuarine waters of South Carolina and Georgia were considered relatively pristine with respect to environmental quality issues such as eutrophication, contamination, and disease-causing organisms. However, land use impacts may begin without obvious warning signs, and become difficult to reverse by the time they are documented. The present dataset documents that anthropogenic activities are increasing nutrient loads to at least one Georgia estuary in a region undergoing escalating population growth; this eutrophication may also be associated with other changes in environmental quality (Fletcher et al., 1998).

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